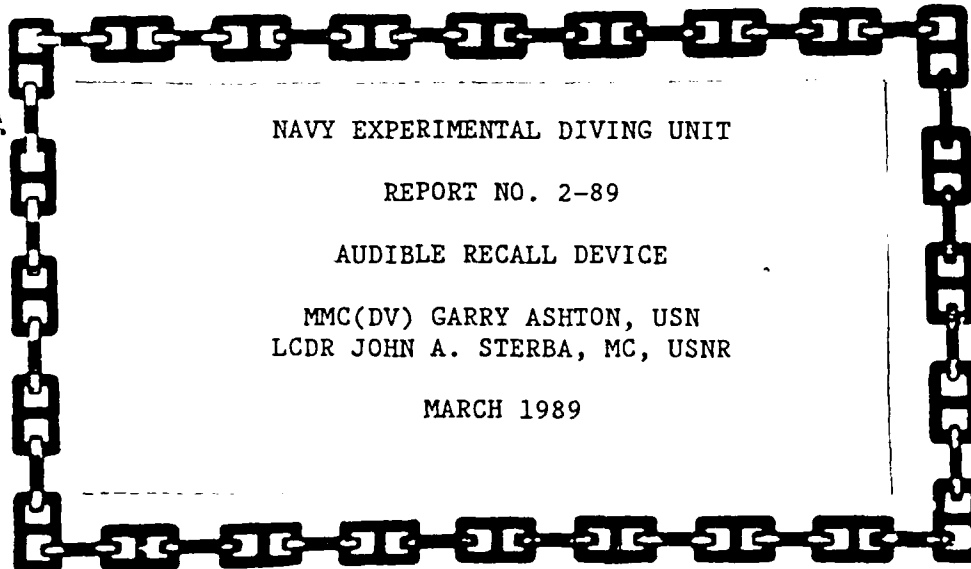


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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 2-89

AUDIBLE RECALL DEVICE

MMC(DV) GARRY ASHTON, USN
LCDR JOHN A. STERBA, MC, USNR

MARCH 1989

NAVY EXPERIMENTAL DIVING UNIT

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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 2-89

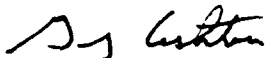
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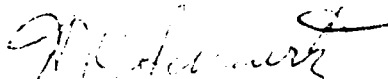
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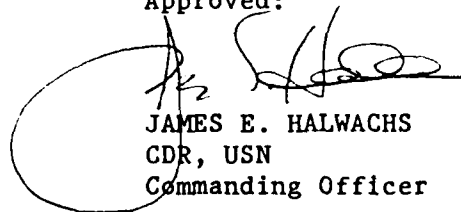
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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The modified Audible Recall Device (ARD) is a small explosively-loaded device designed to be used as an emergency diver recall device by the Special Warfare and Explosive Ordnance Disposal communities. The modified ARD was designed to reduce the acoustic and fragmentation hazards identified by the Navy Experimental Diving Unit (NEDU) during evaluation of the original ARD (NEDU Report 10-87). The modified ARD incorporates a 6.6 sec delay fuse and contains a sand and steel powder mixture to produce a negative buoyancy with average detonation depth approximately 3.38 m (11 ft) underwater. During evaluation of the original ARD, five U.S. Navy divers were exposed to ARD's at 7 m (21 ft) which produced a peak sound pressure level (SPL) of 156.2 dB (re-20 uPa) in water, equivalent to an in-air value of 151.2 dB, 11.2 dB over the current exposure limit for impulse noise, in air, established by OPNAVINST 5100.238. The				
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impulse was described as very loud but not uncomfortable and none of the diver-subjects experienced any decrease in hearing sensitivity as tested by comparison audiograms. The distance for a modified ARD to produce 186.2 dB in 3.38 m (11 ft) of water (re 20 uPa) was found to be 6 m (19.5 ft). The distance for a modified ARD to produce 175 dB in water, equivalent to 140 dB in air, (re to 20 uPa), the limit currently imposed by OPNAVINST 5100.23B was calculated to be 21.2 m (68.9 ft). Actual testing at this distance was not possible due to size limitations of the test facility. However, testing at 20.0 m (65 ft) produced 176.8 dB (re 20 uPa) which was very close to the calculated value at that distance, lending a high degree of certainty to the formulas used.

During standard in-water detonation of modified ARD's, fragmentation was found to travel a maximum distance of 0.36 m (1.2 ft). Observing the minimum standoff distance of 6 m (19.5 ft), this fragmentation poses no apparent risk to divers. When detonated above water, such as an inadvertent activation on a diver support craft, projectile debris travels up to 6.5 m (21.4 ft). This projectile debris consisted predominantly of the rubber insert, outer paper tubing, and a few pieces of the metalized primer assembly. These fragmentation pieces can permanently indent neoprene placed .3 m (1 ft) from a modified ARD but actual injury causing potential of the fragmentation cannot be determined at NEDU.

Despite potential hazards from a mishandled ARD, the device can be used with relative safety, where operational requirements preclude the use of electronic recall systems. All handlers must be thoroughly trained in proper use of the ARD, hazards of misuse, and strictly adhere to prescribed safety precautions.

GLOSSARY

ARD	Audible Recall Device
c	velocity of sound
dB	decibel
msec	millisecond
NAVSEA	Naval Sea Systems Command
NCSC	Naval Coastal Systems Center
NEDU	Navy Experimental Diving Unit
P	density of water
P _m	measured sound pressure
P _{ref}	referenced sound pressure
psi	pounds per square inch
(re 20 uPa)	sound pressure has been referenced to 20 uPa
sec	second
SPL	sound pressure level
SPL _{air}	sound pressure level measured in air
SPL _{water}	sound pressure level measured in water
uPa	micro pascals
Z	impedence of water



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I. INTRODUCTION

The Navy Experimental Diving Unit (NEDU) has been tasked by Naval Sea Systems Command (NAVSEA) to evaluate a modified version of the Audible Recall Device (1). The original Audible Recall Device (ARD) evaluated at NEDU in 1987 was determined unsafe for use by U.S. Navy divers due to risk of shrapnel (2). The original ARD was tested to determine sound pressure levels (SPL) and sound frequency and it was determined to be acoustically safe at a minimum standoff distance of 7 m (22.9 ft). During testing there was strong concern pertaining to fragmentation produced should an ARD inadvertently detonate in air. Further testing was conducted, and the severe fragmentation hazard associated with the ARD subsequently led to NEDU determining the device too hazardous for use.

The Naval Surface Warfare Center, White Oak Laboratory, Silver Spring, Maryland, undertook a program to redesign the ARD to reduce the identified hazards and produce a device which could be used for emergency recall of divers with relative safety where operational requirements preclude use of approved electronic recall systems. Fleet units unofficially report using the detonation simulator M-80 to acoustically recall divers. In addition to the M-80 being a class "A" explosive, it is difficult to use, is unreliable, and has safety and administrative problems.

The proposed alternative, a modification of the original ARD, produced by Propellex Corp., Edwardsville, IL, is a class "C" explosive device using a 6.6 second delay fuse actuated by a sharp pull of a lanyard. This delay provides ample time for the device to be thrown overboard. Weighted with a sand and steel powder mixture to provide negative buoyancy, the modified ARD sinks to approximately 11 feet before detonation.

The principle changes incorporated into the modification of the original ARD include:

1. Material change for the outer case to a kraft paper.
2. Replacement of the glue slug at the end of the original ARD with a chipboard disc.
3. Reduction in explosive loading of the primer from 1.0 gram to 0.75 grams.
4. Replacement of the lead shot ballast with a fine steel powder and a configuration change separating this component from the explosive.

Current U.S. Navy instructions (3), stipulate the safe exposure limit to impulse noise as 140 dB which is an in-air value referenced to 20 micro pascals (re 20 uPa). As explained in detail in the Methods Section, 140 dB in-air is equivalent to 175 dB in-water (re 20 uPa). Recent studies performed at NEDU (2, 4) demonstrated that divers could be exposed to levels as high as 186.2 dB in-water with no reduction in hearing sensitivity as measured by audiograms prior to and following exposure to ARD's. Therefore, the

objectives of this project were to find a minimum safe standoff distance a diver must be from a modified ARD for exposure to 186.2 dB in-water (re 20 uPa), demonstrated to be a safe limit. Also, to determine what distance a modified ARD will produce 175 dB in-water, equivalent to the 140 dB in-air standard. As diver safety is also a factor of the sound frequency of explosion, accurate measurements were made to ensure the frequency range of a modified ARD were above the 50 Hz level known to cause injury to lung tissue (5). Finally, detailed fragmentation studies were conducted to determine if the modifications to the original ARD had in fact reduced the fragmentation hazard to a relatively safe level.

II. METHODS

A. BACKGROUND

To provide for direct comparison to the evaluation conducted of the original ARD, the unmanned portions of that study (2) were duplicated as closely as possible. Reproduction of the manned portions of that study, which served to establish safe exposure limits for divers, were unnecessary. One noteworthy difference was in testing the fragmentation risk. A plastic sheet (0.006 inch thickness) perimeter was circular vice square to produce a uniform horizontal distance to all points from the modified ARD.

B. ACOUSTIC MEASUREMENTS

The Naval Coastal Systems Center (NCSC) in Panama City, FL provided use of the Acoustic Test Facility for unmanned testing of the modified ARD. The Acoustic Test Facility is a 6.1 m (20 ft) deep fresh water pond at 23.8°C (75°F) water temperature with a centrally placed pool liner allowing both filtration and chlorination of the acoustic test pool area. The gantry and walkways were structurally outside the pool area reducing noise artifact. During testing of the modified ARD, one wide band tourmaline gauge hydrophone was used to record the impulse on a magnetic floppy disk. The sound pressure level was immediately measured and frequency spectral analysis was performed by storing the waveform of the impulse on a storage oscilloscope (Nicolet Model 2090, Madison, WI). This frequency information was later analyzed by transferring the Nicolet floppy disk data to a Hewlett Packard computer (Model 520, Corvallis, OR).

All ARD's were exploded at the same depth (11 ft) to acoustically avoid the thermocline at approximately 3 m (9.8 ft). Hydrophones were also maintained at a constant depth of 3.69 m (11 ft). Due to the initial long distances (20 m, 65 ft) from the exploding ARD's, the ARD's were fired outside the pool liner in the pond water, with the hydrophone inside the pool liner. Earlier tests verified that the pool liner did not alter the SPL or the frequency spectral analysis of these shots. Furthermore, orientation of the ARD underwater did not influence peak sound pressure level (SPL) or frequency spectrum of the ARD impulse.

C. MEASUREMENT OF SOUND UNDERWATER

Sound is measured with the SPL measured in decibels (dB). SPL is actually a logarithmic ratio of the measured sound pressure (P_m) divided by reference sound pressure (P_{ref}) in equation [1].

$$SPL(dB) = 20 \log (P_m/P_{ref}) \quad [1]$$

In air, P_{ref} is 20 micro pascals (20 uPa) sound pressure which is also equivalent to 0.0002 dyne/cm² sound pressure. In water, the usual reference is 1 uPa sound pressure. However, with only air impulse noise research and standards to follow due to a lack of research in underwater impulse noise, our underwater SPLs were referenced to 20 uPa (re 20 uPa) based on $20 \times \log (20/1) = 26$ dB, in equation [2].

$$SPL_{water} (re 1 \text{ uPa}) - 26 \text{ dB} = SPL_{water} (re 20 \text{ uPa}) \quad [2]$$

U.S. Navy Instruction (3) defines hazardous noise as sound pressure in-air in excess of 140 dB (re 20 uPa). Therefore, in order to convert SPL in water (SPL_{water} re 20 uPa) to an equivalent sound pressure level in air (SPL_{air} re 20 uPa), one must correct for the density of water (p) and velocity of sound (c) in order to calculate the acoustic impedance of water (Z) based on equations [3] and [4].

$$p \cdot c = Z \quad [3]$$

$$SPL_{air} (re 20 \text{ uPa}) = (SPL_{water})^2/Z \quad [4]$$

To correct for the acoustic impedance difference in water and air, use equation [5] below which subtracts 35 dB from SPL_{water} to give SPL_{air} (4, 6).

$$SPL_{water} (re 20 \text{ uPa}) - 35 \text{ dB} = SPL_{air} (re 20 \text{ uPa}) \quad [5]$$

Thus, 175 dB (re 20 uPa) in-water equals 140 dB (re 20 uPa) in-air.

To convert a SPL in dB to units of pounds per square inch (psi), the following equation, [6], is used according to Zimmerman and Lavine, 1955 (7).

$$psi = \text{Antilog} [(SPL \text{ re } 20 \text{ uPa} + 26)/20] \times 1.45 \times 10^{-10} \quad [6]$$

The literature describing the positive deflection of the impulse known as the A Impulse explains how the area under the A Impulse waveform can be approximated using Friedlander equation [7] below (8, 9).

$$[\text{Pressure (PSI)} \times \text{Duration of A Impulse (msec)}] / \text{exponent } e \text{ or } 2.718 = \text{Impulse (psi} \cdot \text{msec)} \quad [7]$$

The criteria for safety of an unprotected swimmer takes into account SPL in psi, duration in milliseconds (msec), and frequency range. Guidelines state that exposure to impulse noise must be less than or equal to 2 psi·msec

and the peak over pressure must be less than or equal to a SPL of 100 psi (10, 11). It is also believed that an unprotected swimmer could possibly tolerate up to 10 psi•msec, but research has demonstrated minor small blood vessel damage to the lungs and gastrointestinal tract. As reported, these injuries were not considered life threatening and were determined to be acceptable minor injuries under some operational conditions (11). Recent studies at NEDU demonstrated that divers could be exposed to a SPL of 186.2 equivalent to 5.85 psi, with a duration of 1 msec which calculates to 2.173 psi•msec based on equation [7] without acoustic injury. Therefore, for the purpose of this study, 2.17 psi•msec was used as the uppermost safe exposure limit.

From animal research (5), the natural oscillation frequency of lung tissue has been found to be approximately 50 Hz. A determination of the frequency range of the modified ARD was also performed to insure it was above this hazardous range.

D. FRAGMENTATION STUDIES

1. Air Detonation Tests

Since it is a possibility that an ARD could inadvertently detonate aboard a diver support platform, a study to determine the fragmentation hazard above water was undertaken. A metal frame was constructed to hold the ARD in a vertical position 2 feet from the ground. This frame also provided for fairleading of a line to achieve remote activation of ARD. A circular perimeter of plastic (Visqueen, 0.006 inches thick) was constructed to absorb fragmentation particles. This perimeter started at a distance of 1 foot from the ARD and was moved outward in 1 foot increments. Figure 1 shows the standard orientation for the test equipment.

During testing of the original ARD the end cap assembly proved to be the most significant piece of fragmentation. In testing the modified ARD a separate test was performed to determine whether the change of design of this end cap subassembly had reduced the distance this piece would travel. As shown in Figure 2, an ARD was held in place and aimed over water at 45° above horizontal. The ARD was remotely initiated and a determination of the distance traveled by the end cap sub assembly was conducted by observing the splash down of the assembly in the water.

An ARD was also initiated at 1 foot from a neoprene suit to determine if the fragmentation could penetrate a wetsuit type material. The 1 foot distance was chosen as a worse case scenario of an ARD detonation while being held by an individual.

2. In-Water Detonation Tests

As the ARD is designed to detonate underwater, a determination of the fragmentation hazard to a diver was conducted. It was intended to duplicate the dry land testing procedures until no fragmentation was recorded on the witness sheet. This was done at a 1 foot depth underwater to simulate a worse case situation in the lowest density of water.

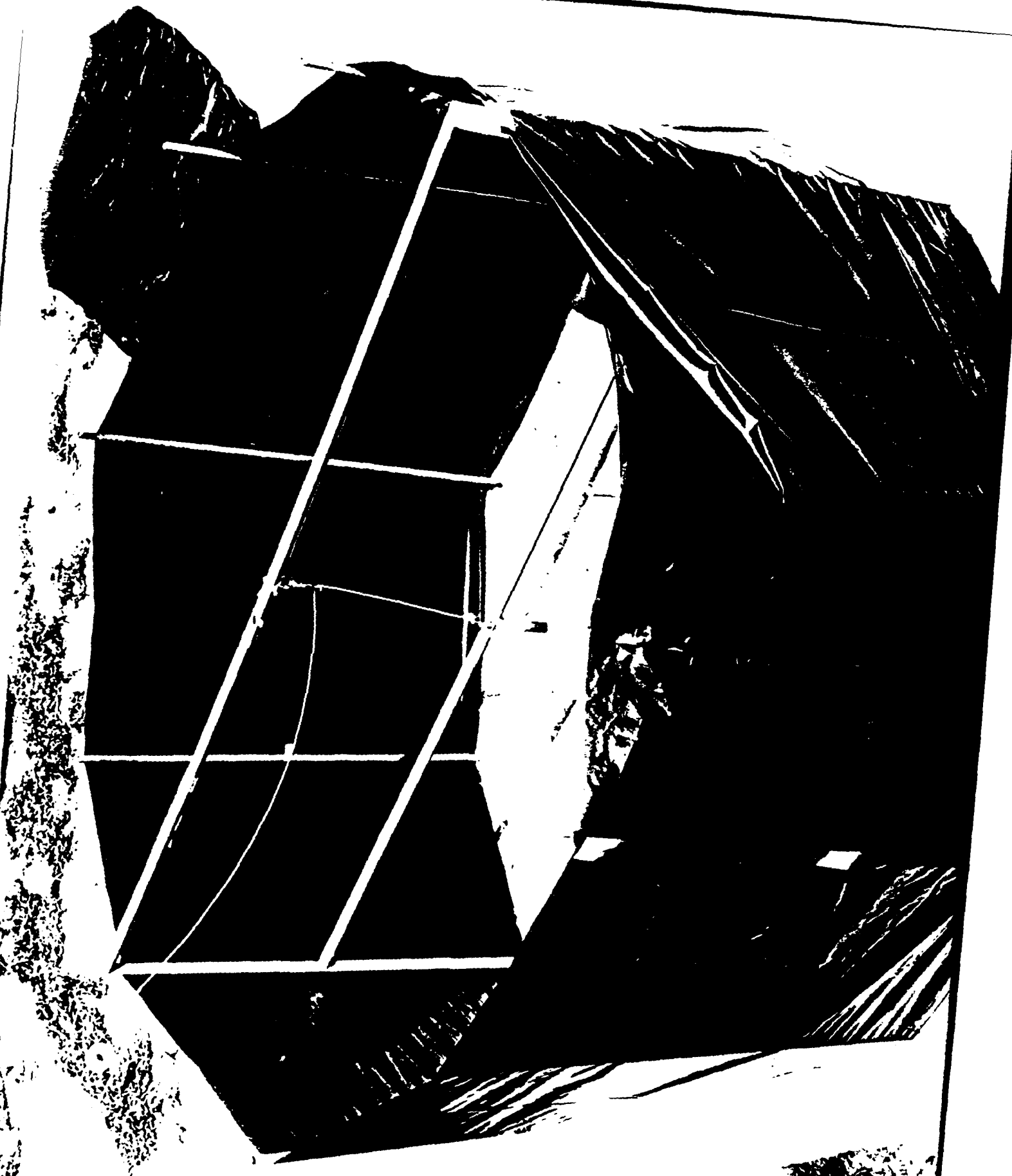


Figure 1. Standard Equipment Orientation for Air Fragmentation Studies



III. RESULTS

A. UNMANNED ACOUSTIC TESTING

TABLE 1

Results of SPL Testing
for Modified ARD

<u>Distance (m)</u>	<u>SPL in dB</u> (re 10 uPa)	<u>n = number of tests</u>
2	195.5 ± 1.1	n = 3
5.5	187.2 ± 0.5	n = 2
6	186.0 ± 0.3	n = 3
7	184.5 ± 1.1	n = 4
8	183.6 ± 0.0	n = 1
17	177.2 ± 0.2	n = 2
18.5	178.6 ± 0.7	n = 2
20	176.8 ± 2.5	n = 4
*21.2	175	

* Actual testing could not be performed at this distance due to size limitations of the test facility. The distance to produce 175 dB was calculated based on results from all other distances.

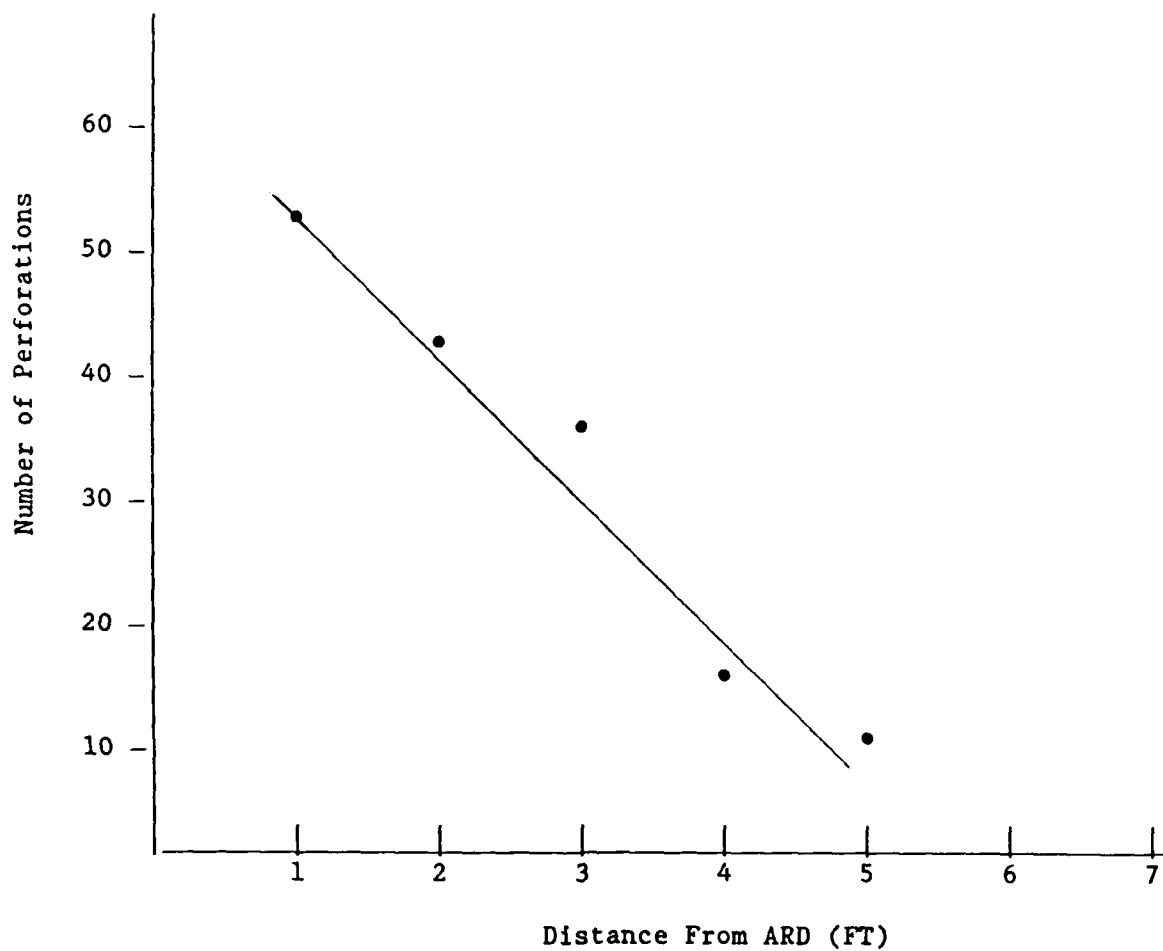
TABLE 2

Peak Frequencies Exhibited by the Positive Wave (A Wave)
for Modified ARD

<u>Distance (m)</u>	<u>Peak Frequency (Hz)</u>	<u>n = number of tests</u>
2	463	n = 3
5.5	475.5	n = 2
6	731.5	n = 3
7	744	n = 2
8	Not Tested	
17	Not Tested	
18.5	Not Tested	
20	1317	n = 4

NOTE: Although the peak frequencies varied considerably, all were considerably above the 50 Hz range known to cause lung tissue damage (5).

B. IN-AIR FRAGMENTATION STUDIES



NOTE: Testing beyond 5 feet was not accomplished due to the limited number of ARD's available for test.

Figure 3. Number of Fragments Perforating the Witness Sheet Measured in Air

C. UNDERWATER FRAGMENTATION STUDIES

It was found that underwater fragmentation traveled a maximum of 0.35 m (1.2 ft) and failed to penetrate the witness sheet at the closest distance tested in water, 0.3 m (1 ft).

IV. DISCUSSION

This study establishes two values for safe standoff distances for divers from a modified ARD. The ARD functioned at 6 m (19.5 ft) produced 186.0 dB (re 20 uPa). For all practical purposes, this is equivalent to the level divers were exposed to in past studies at NEDU (2, 4). None of the divers exposed to levels as high as 186.2 dB in those studies showed any permanent damage to hearing even though this 186.2 dB is equivalent to 11.2 dB above the in-air maximum exposure limit by Navy instructions (3). It is believed that a 6 m (19.5 ft) underwater safe standoff is appropriate for the modified ARD. Navy instructions (3) currently state that the safe exposure limits for impulse noise is 140 dB in-air, equivalent to 175 dB in-water. The distance required for a modified ARD to produce 175 dB is calculated to be 21.2 m (68.9 ft). Actual testing was limited to 20 m (65 ft) due to the size of the test facility, but the 21 m (68.9 ft) distance can be calculated with a high degree of certainty using values obtained at shorter distances.

The frequency levels produced by the modified ARD were difficult to precisely determine due to the large area of the peaks and the energy produced covered a broad acoustic spectrum. As in earlier studies (2), it was felt that for this study, only the positive wave (A wave) should be examined. The negative wave, being a reflective entity, varies with every shot and is dependent upon variables such as water temperature, depth, thermoclines, and surrounding structures. As stated, the maximum frequency ranges varied considerably, 450 - 550 Hz at 6 m (19.5 ft) up to 1100 - 1300 Hz at 20 m (65 ft). What is important to note is that there was no significant energy produced in the 50 Hz range known to produce lung tissue damage (5).

It has been demonstrated through unmanned and manned studies that divers can safely withstand pressure levels as high as 2.17 psi•msec. This is the level produced by the modified ARD at the 6 m (19.5 ft) underwater safe standoff distance.

Since the above water fragmentation hazard associated with the original ARD was the primary factor in the original ARD being considered too hazardous for use, emphasis was placed on accurate determination of fragmentation production of the modified ARD. The tests were done at varying distances, representative of distances personnel may be situated aboard a diver support craft. The 1 foot test against a neoprene suit simulates a worse case scenario of an ARD detonation while being held by topside personnel. The modified ARD does produce fragmentation, an inherent property of all explosive devices. There has been a significant reduction in the mass and distance traveled by the fragmentation from the modified ARD as compared to the predecessor, the original ARD. Although pieces of the modified ARD perforated

the 0.006 inch thick plastic witness sheet at a distance of 5 feet and pieces were found to travel up to 6.5 m (21.4 ft) the injur, causing potential of this fragmentation cannot be determined at NEDU. The selection of 0.006 inch thick plastic sheet was in no way an attempt to duplicate the perforation of skin tissue, but simply to provide for direct comparison to results of original ARD testing which used this witness material. Underwater studies proved that the fragmentation hazard was negligible at distances as close as 0.3 m (1 ft). Observing the minimum safe acoustic standoff of 6 m (21.4 ft), this fragmentation poses no apparent risk to divers.

It has been learned through research for this project that there are at least two different portable diver recall devices currently in use by different NATO countries. It may prove beneficial to conduct a market survey and direct comparison study of all portable recall devices to determine the most practical and least hazardous device for use.

V. CONCLUSION

The Audible Recall Device is intended as an emergency signal used to prevent exposure of divers to potentially hazardous situations. Bearing this in mind, the risk of a mishandled ARD should be considered acceptable as compared to the possible injury or death of divers due to a lack of an adequate recall system. Despite the potential hazards from a mishandled ARD, the device can be used with relative safety where operational requirements preclude use of electronic recall systems provided that:

A. All handlers are thoroughly trained in proper use of the ARD and potential hazards of misuse.

B. All handlers strictly adhere to prescribed safety precautions.

C. A warning statement be added stipulating that 6 m (19.5 ft) is the minimum safe underwater standoff from an ARD to a diver.

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